Zero-Carbon Gas-Turbine Power and Propulsion

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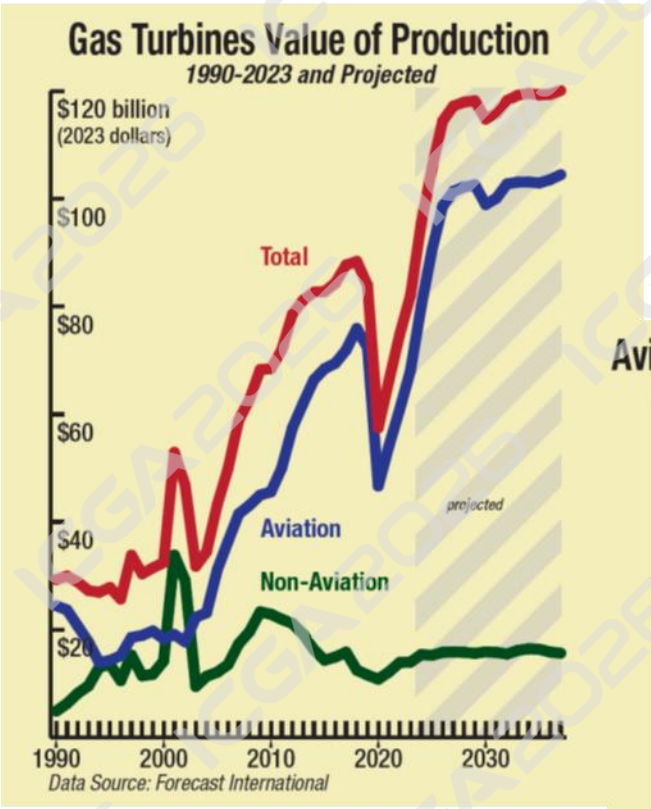
Prepared for

Fourth International Conference on Green Aviation

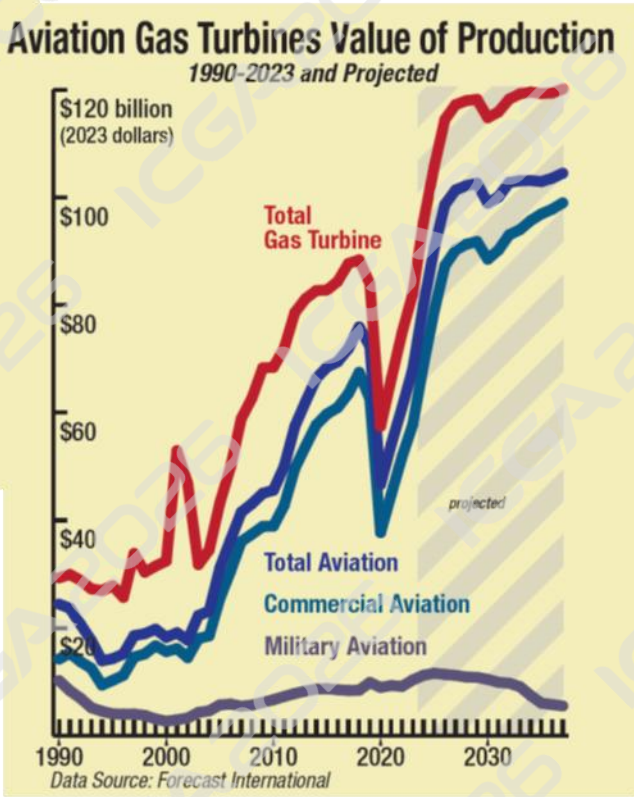
November 3, 2026

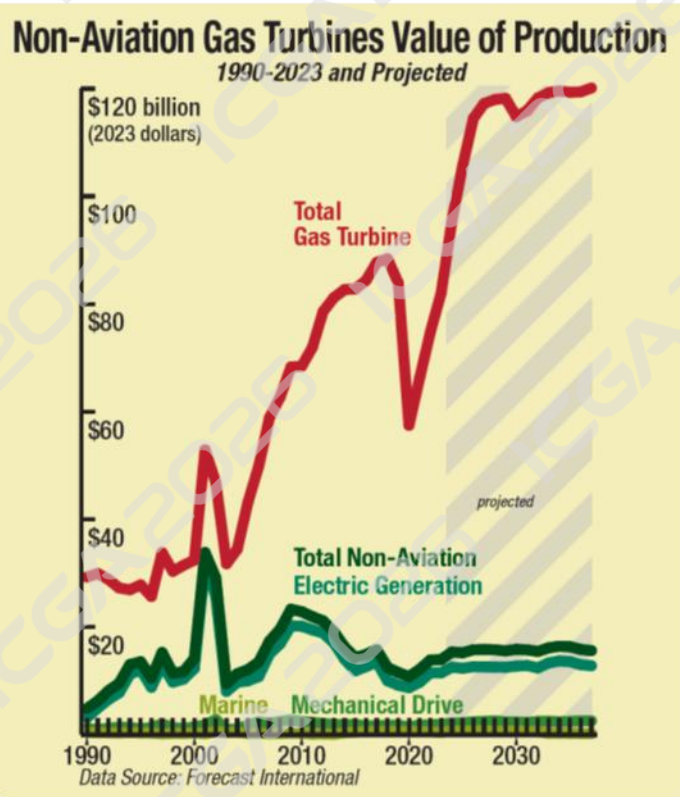
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Gas Turbine Global Value of Production Trends



- Power generation gas turbines contribute ~10% CO_2 emissions in US.
- Aviation contributes 3%++ of anthropogenic CO_2 emissions.
- Shipping CO_2 emissions similar level as aviation.

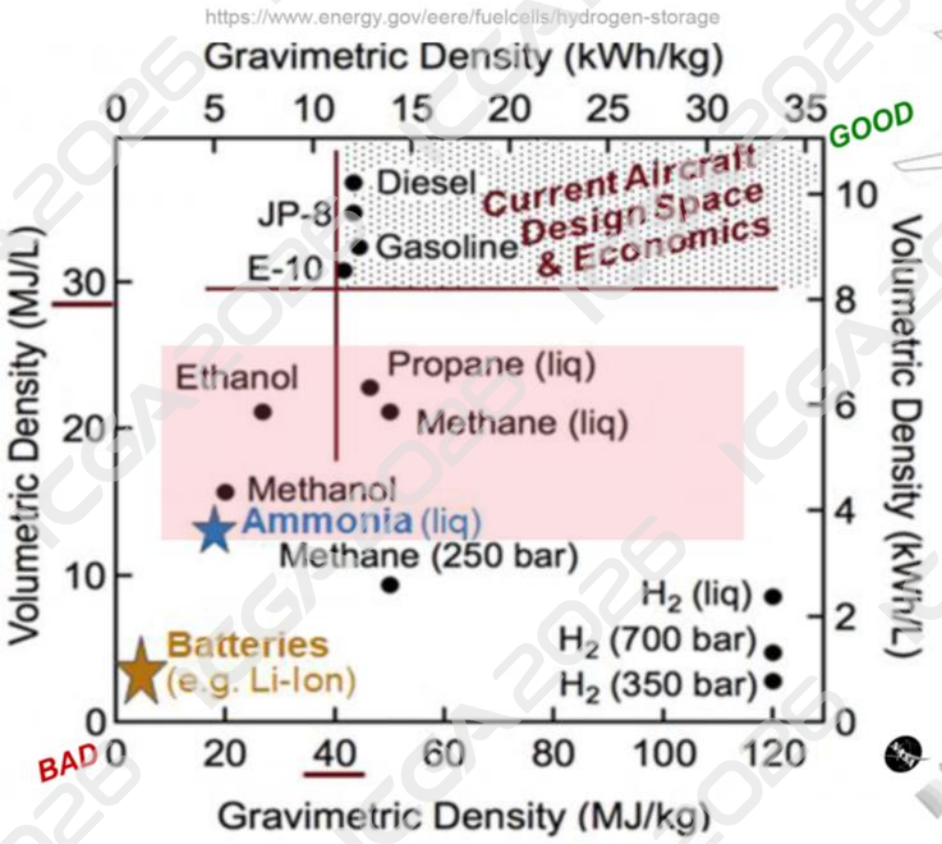


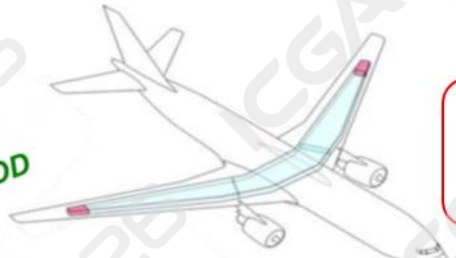


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"Net-Zero Carbon" Fuel Options in Aviation: Volume and Weight







Carbon-Free Fuels

- Hydrogen
- Ammonia

- SAF with low life cycle carbon emissions
- "Low"-Carbon Fuels
  - LNG
  - Methanol
- (Batteries)

- Ammonia's energy similar to methanol
- Ammonia's storage properties similar to propane
- Ammonia ⇒ "familiar" fuel

- Global jet fuel use: ~200B kg/year
- Global NH_3 production: ~175B kg/year; 2nd most transported chemical in world

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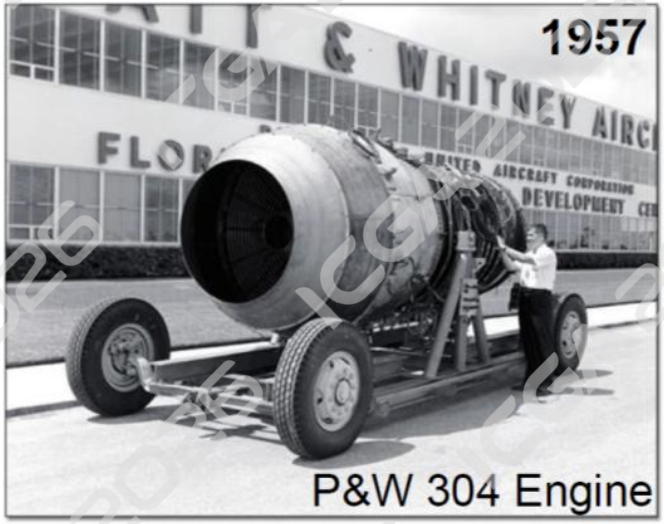
H_2- and NH_3-based Engines (1)

Early Cold-War Era



NASA X-15

- *NH_3 fueled rocket engine*



Project Suntan

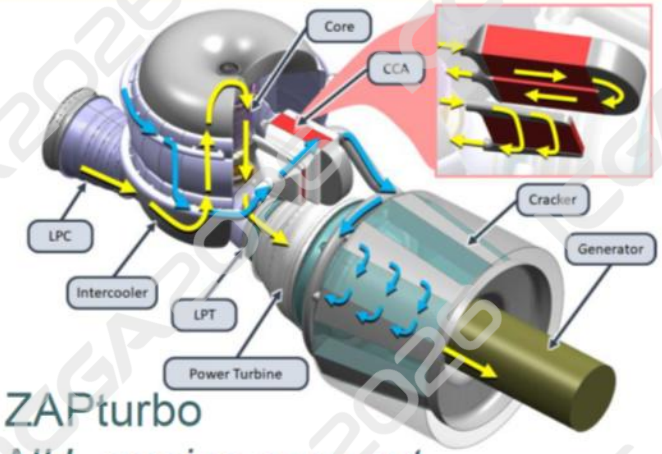
- *H_2 turbine engine, predecessor to RL10 rocket engine*

- High-altitude, High-speed flight

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H_2- and NH_3-based Engines (2)

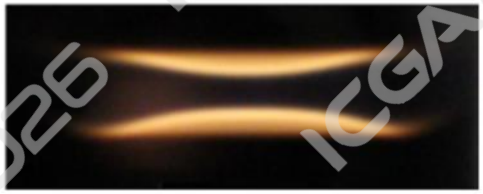
Climate-Change Era



ZAPturbo
NH_3 engine concept



"LOAD-Z" DOE
NH_3 combustion studies



HySIITE *H_2 engine concept*



- Low carbon, Low climate-impact flight

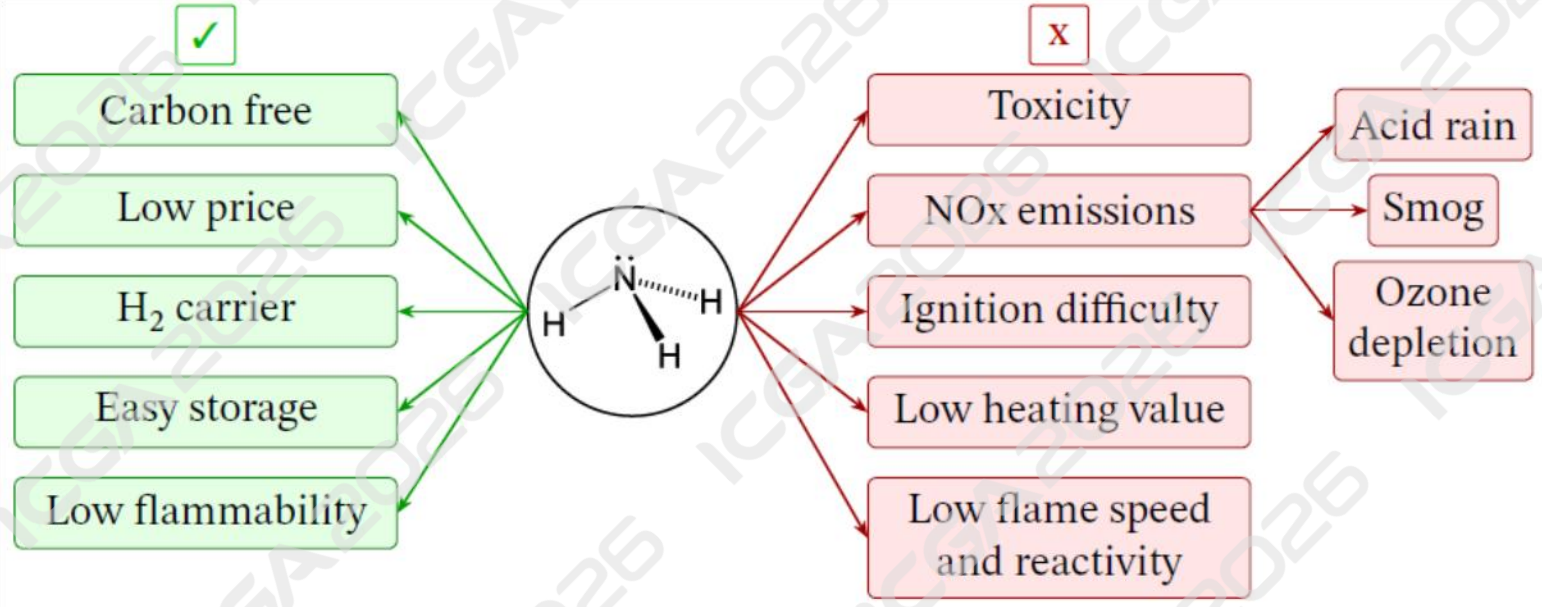
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Challenges: How to Burn NH_3 with Low Emissions (1)

- Liquid-NH_3 contains more than 1.5 times the energy of liquid-H_2 per unit volume.



- A major challenge is emissions of nitrogen oxides (NO, NO_2, N_2O, N_2O_3, etc.), collectively called NO_x, from ammonia combustion.

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Challenges: How to Burn NH_3 with Low Emissions (2)

- The U.S. EPA regulates gas turbine emissions – for example, the NO_x emission limit for new natural gas-fired stationary turbines (>249 MW) is 15 ppm at 15% O_2.
- There are many factors that impact NO_x formation in gas turbines.

$$[NO_x] = f\{\text{Temperature}, \text{Pressure}, \text{Equivalence ratio}, \text{Residence time}, \text{Wall heat loss}\}$$

$$NO_x \equiv NO + N_2O + NO_2$$

- Chemical kinetic studies are crucial for designing low-NO_x ammonia combustors.

Can ammonia combustor design achieve <15 ppm NOx under gas turbine-relevant combustion conditions?

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Acknowledgements

- In collaboration with Dr. Lance Smith, Dr. Paul Papas, and Dr. Zhongtao Dai, RTX Technology Research Center
- UConn graduate students: Satyendra Rana, Rouzhou Fang, and James Stevens
- Recent Publications –
  - S. Rana, P. Papas, L. L. Smith, and C. J. Sung, "Reducing NO_x Emissions in Ammonia Combustors," *Journal of Engineering for Gas Turbines and Power* **148 (1)**, 011015 (2026).
  - J. F. Stevens, R. Fang, B. Rees, I. Pichs, S. Dunn, P. Papas, L. L. Smith, and C. J. Sung, "Counterflow Premixed Ammonia/Air Flame Extinction Limits at Elevated Temperatures and Pressures," *Fuel* **430**, **Part A**, 140999 (2027).
  - Z. Dai, S. Rana, P. Papas, L. L. Smith, and C. J. Sung, "Computational Design Study for Low Emission, Rich-Quench-Lean Ammonia Combustor," *ASME Turbo Expo 2026*, ASME Paper No. GT2026-176628 (2026).

RTRC
RTX Technology Research Center

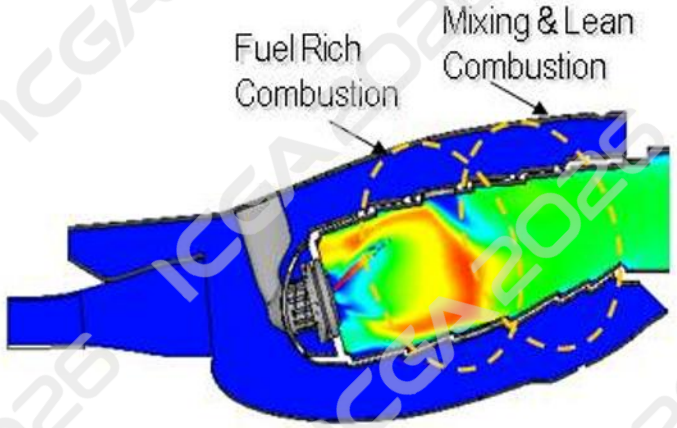
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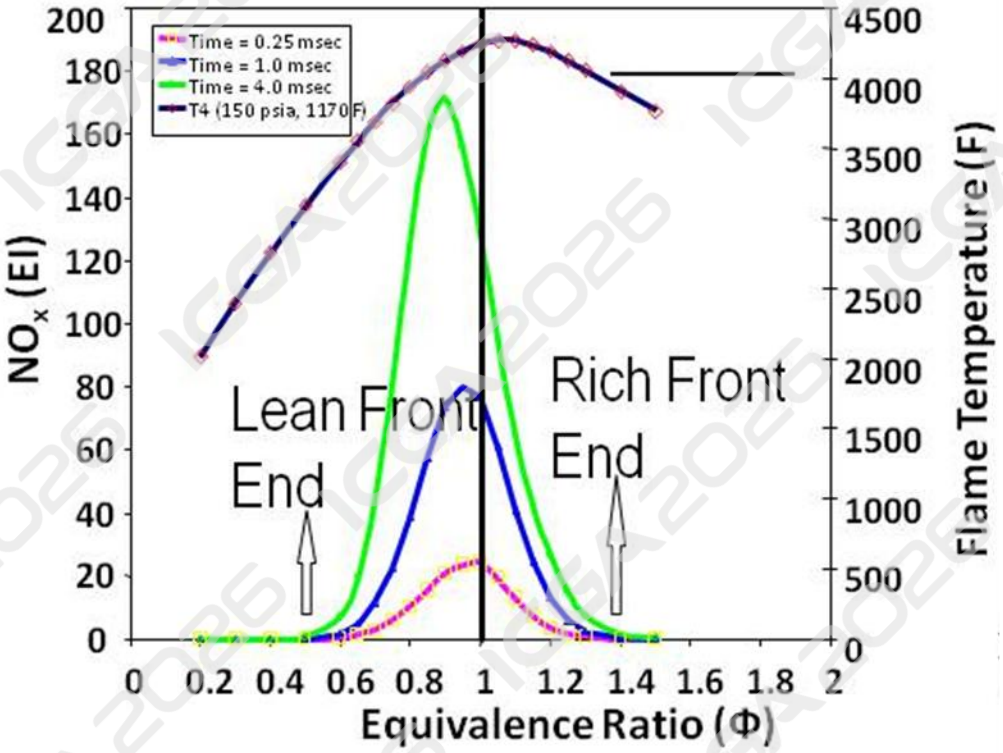
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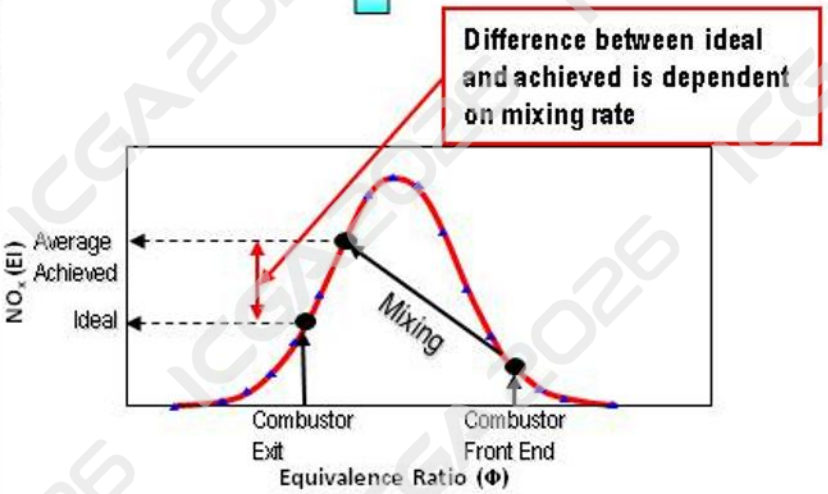
Rich-burn/Quick-quench/Lean-burn (RQL) Concept

- To achieve high efficiency, ultra-low NO_x emissions, and stable operation under varying power conditions, the RQL combustor design widely used in gas turbines has shown promise.





Rich Quick Quench Lean (RQL)

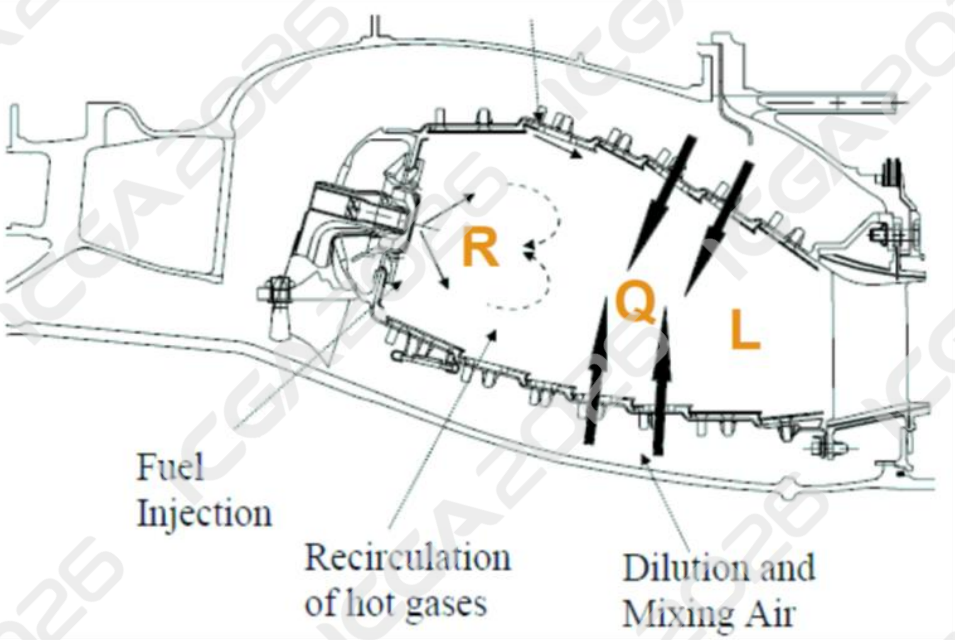


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Re-Think Approach to RQL Combustion (1)

Conventional RQL for Hydrocarbon Fuels



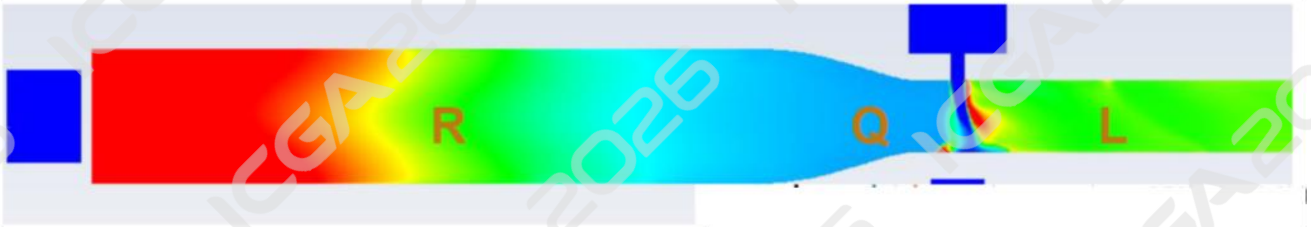
- Rich-zone considerations:
  - PM (soot) vs. turndown
    ⇒ FAR range
  - Ignition/stability
    ⇒ geometry/size ($\tau_{AnchorZone}$)
- Lean-zone considerations:
  - CO burnout vs. NO_x
    ⇒ τ_{Lean} ↑or↓, rapid mixing
  - Pattern factor (temperature uniformity) ⇒ complete mixing

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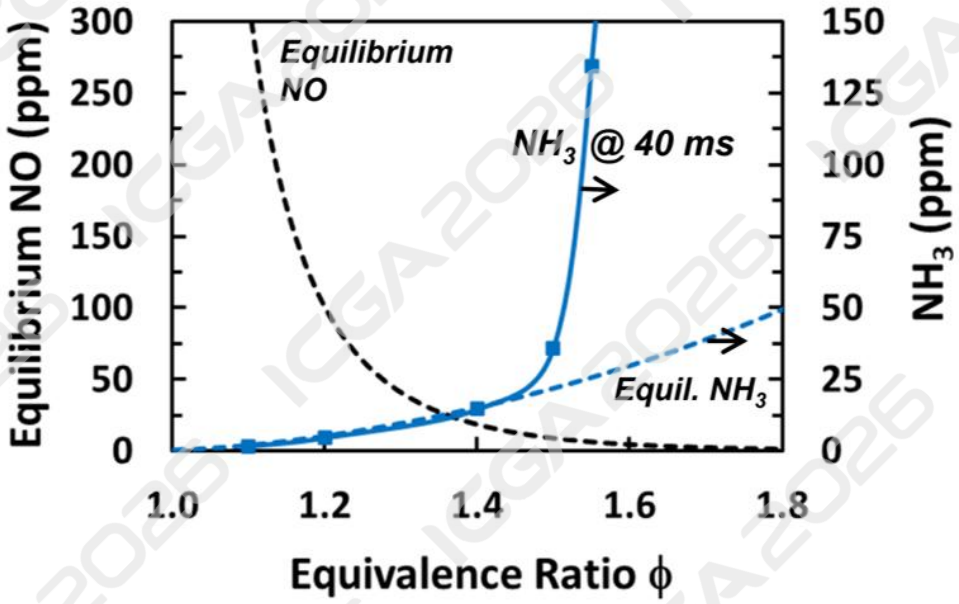
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Re-Think Approach to RQL Combustion (2)

RQL Reconfiguration for Low-NO_x NH_3 Combustion



NH_3-Air Combustion at p = 35 atm, T = 850 K



- **NH_3 at rich conditions (*oxidation* and *cracking*):**
  - At equilibrium ⇒ NH_3<20 ppm for $\phi < 1.4$
  - Remaining fuel is H_2 ⇒ burn at lean-stage air addition
  - NH_3 cracking and oxidation time >> 40 ms for $\phi > 1.5$

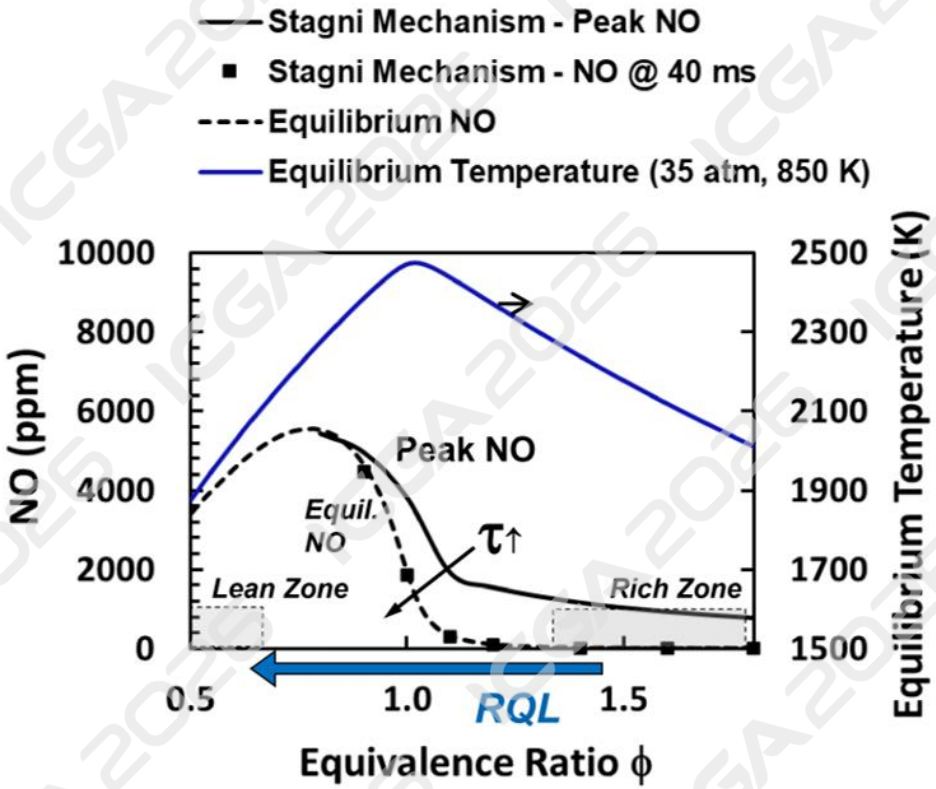
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Re-Think Approach to RQL Combustion (3)

RQL Reconfiguration for Low-NO_x NH_3 Combustion



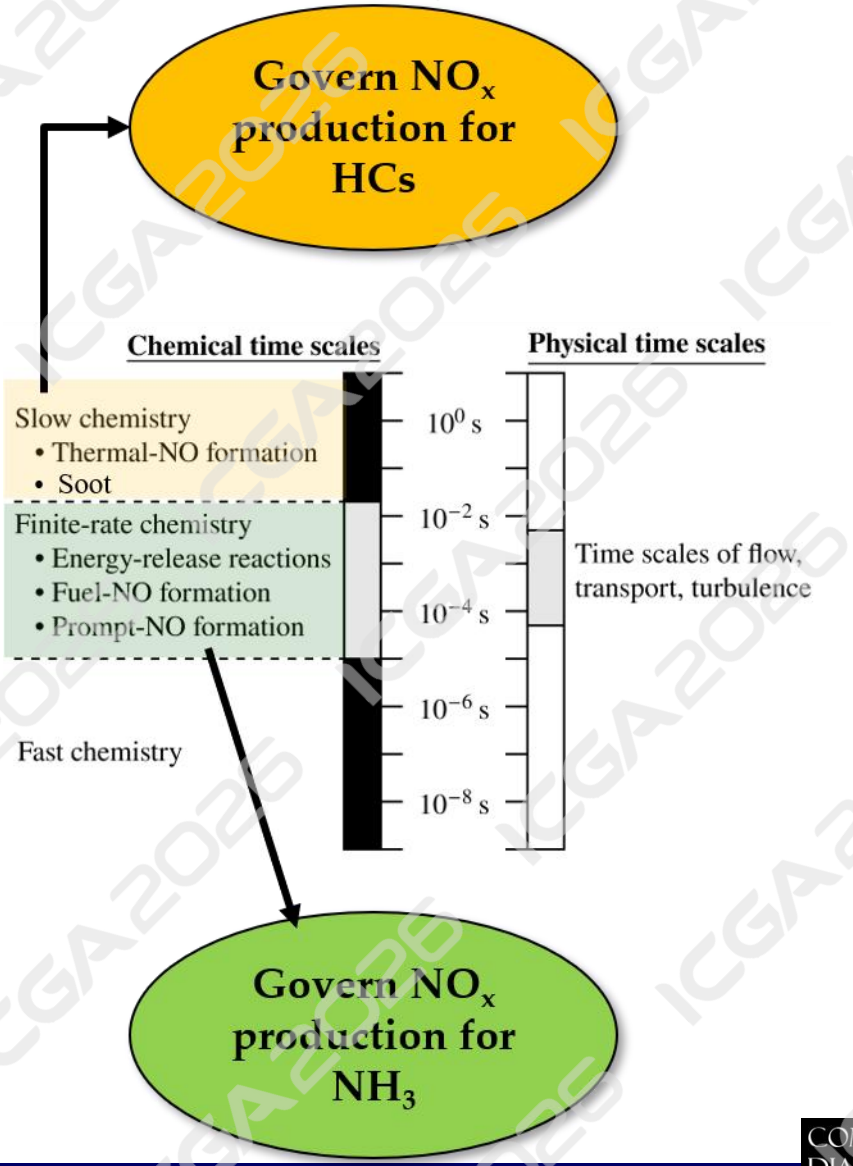


- **NO_x at lean/rich conditions:**
  - N pathway ⇒ starts from both air (N_2) and fuel (NH_3)
  - Approach to equilibrium ⇒ from "above" (versus "below")
  - 10 ppm achievable ⇒ τ_{Rich} and τ_{Lean}

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Challenges of Adopting RQL Concept to NH_3



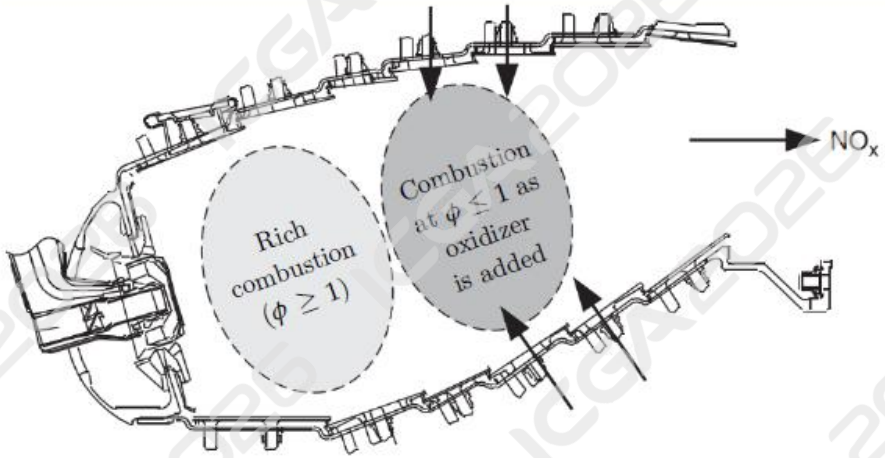
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Chemical Reactor Network (CRN) Modeling (1)

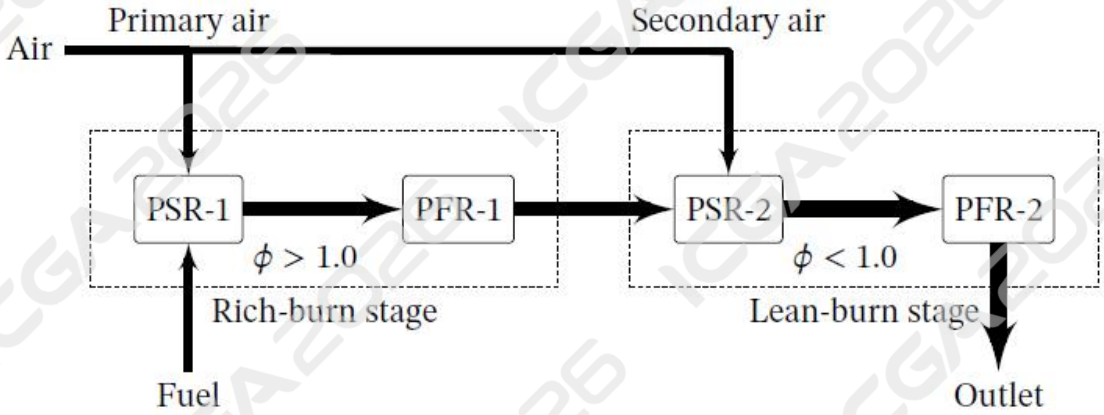
Rich-burn/Quick-quench/Lean-burn (RQL) Combustor



Rich-burn
Mixing & flame: PSR-1
Downstream combustion: PFR-1

Lean-burn
Secondary air mixing: PSR-2
Post-mixing combustion: PFR-2

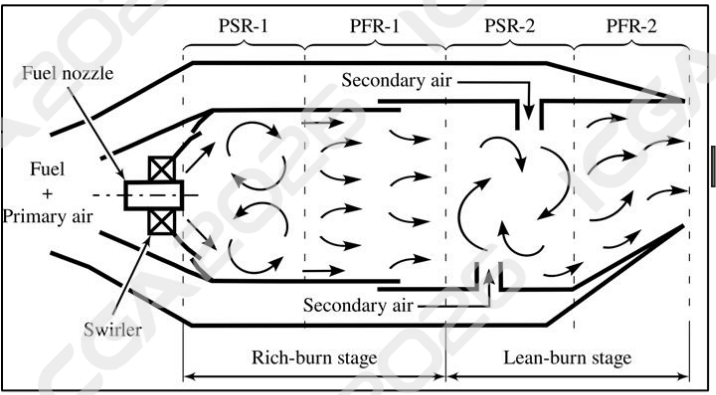
PSR – Perfectly-stirred reactor
PFR – Plug-flow reactor

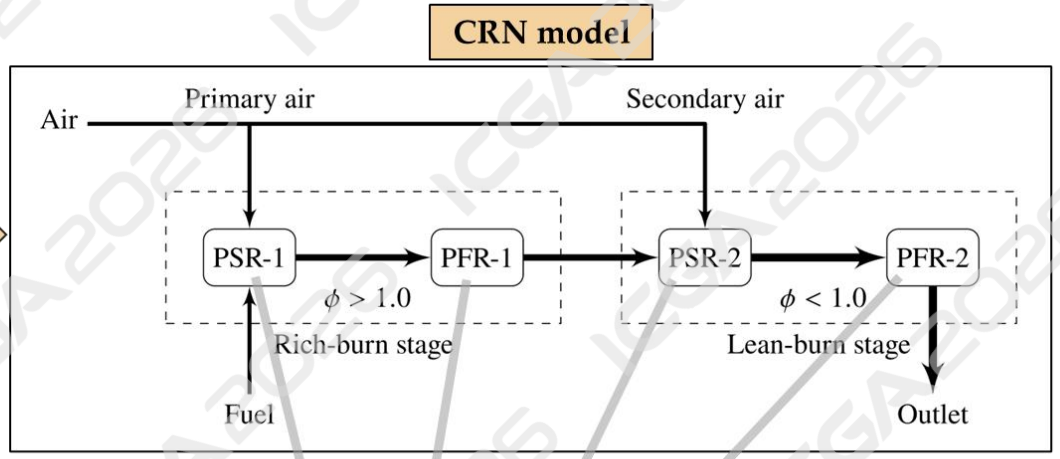


- *Cantera*: Open-source flame and chemical kinetics simulation tool
- CRN: Computationally less intensive than 3D simulations & reliably accurate

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Chemical Reactor Network (CRN) Modeling (2)





PSR: Perfectly-stirred reactor
PFR: Plug-flow reactor

Study set	τ_{total} (ms)	τ_{PSR-1} (ms)	τ_{PFR-1} (ms)	τ_{PSR-2} (ms)	τ_{PFR-2} (ms)	P_{in} (atm)	T_{in} (K)	T_{out} (K)	ϕ_r (-)
A	38.5	0.5	35	1	2	35	850	1800	1.0 – 1.8
E	11.5 – 41.5	0.5	5 – 35	1	2 – 5	20	850	1800	1.0 – 1.8
F	11.5 – 41.5	0.5	5 – 35	1	2 – 5	30	850	1800	1.0 – 1.8
G	11.5 – 41.5	0.5	5 – 35	1	2 – 5	40	850	1800	1.0 – 1.8

Parametric vari

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Chemical Reactor Network (CRN) Modeling (3)

Study set	τ_{total} (ms)	τ_{PSR-1} (ms)	τ_{PFR-1} (ms)	τ_{PSR-2} (ms)	τ_{PFR-2} (ms)	P_{in} (atm)	T_{in} (K)	T_{out} (K)	ϕ_r (-)
								industrial engine "baseline" case	
A	38.5	0.5	35	1	2	35	850	1800	1.0 – 1.8
B	11.5 – 41.5	0.5	5 – 35	1	2 – 5	35	850	1700	1.0 – 1.8
C	11.5 – 41.5	0.5	5 – 35	1	2 – 5	35	850	1800	1.0 – 1.8
D	11.5 – 41.5	0.5	5 – 35	1	2 – 5	35	850	1900	1.0 – 1.8
E	11.5 – 41.5	0.5	5 – 35	1	2 – 5	20	850	1800	1.0 – 1.8
F	11.5 – 41.5	0.5	5 – 35	1	2 – 5	30	850	1800	1.0 – 1.8
G	11.5 – 41.5	0.5	5 – 35	1	2 – 5	40	850	1800	1.0 – 1.8

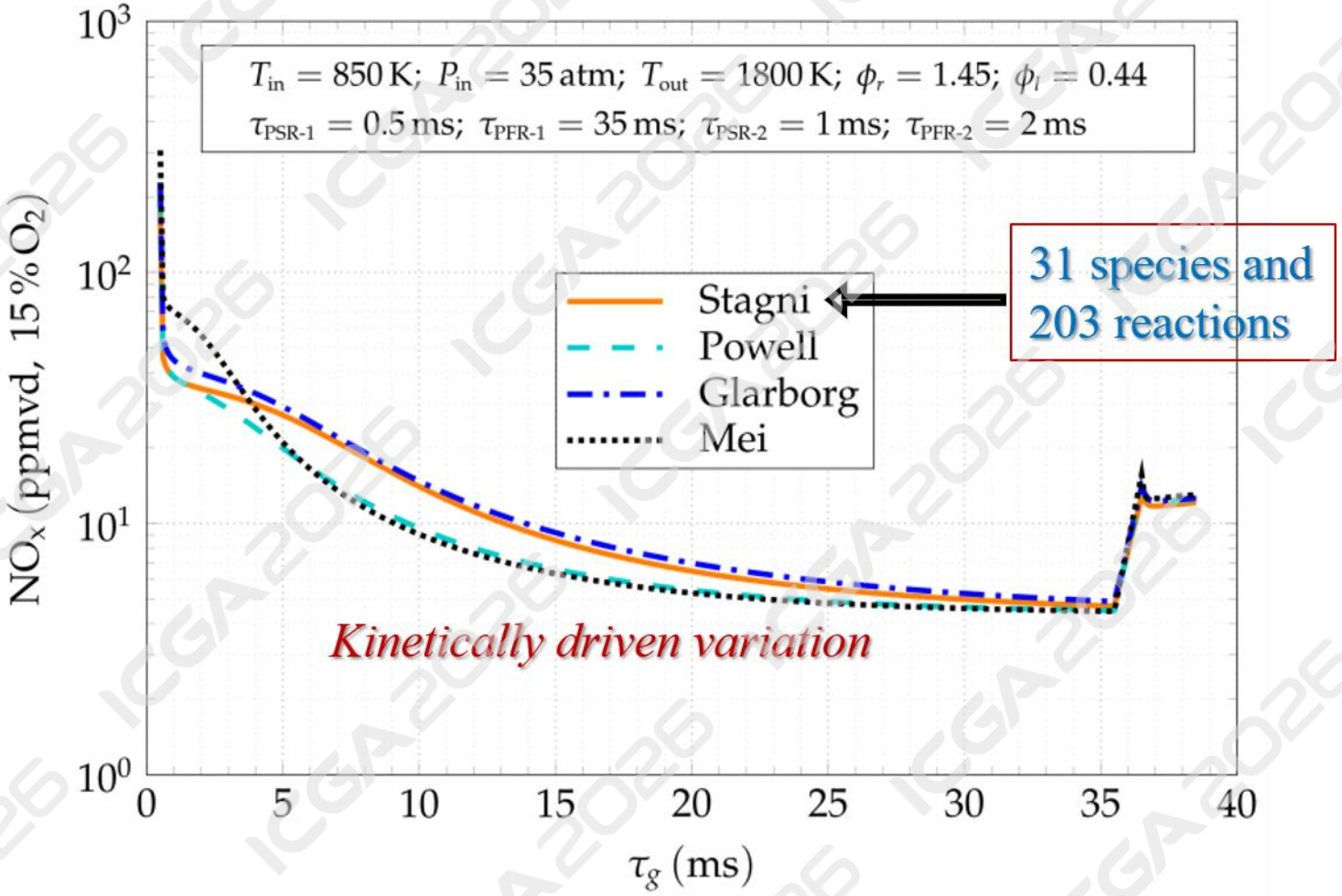
Examine conditions and kinetics for "relaxation" to low emissions

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Chemical Reactor Network (CRN) Modeling (4)

Comparison of Literature Chemical Kinetic Models

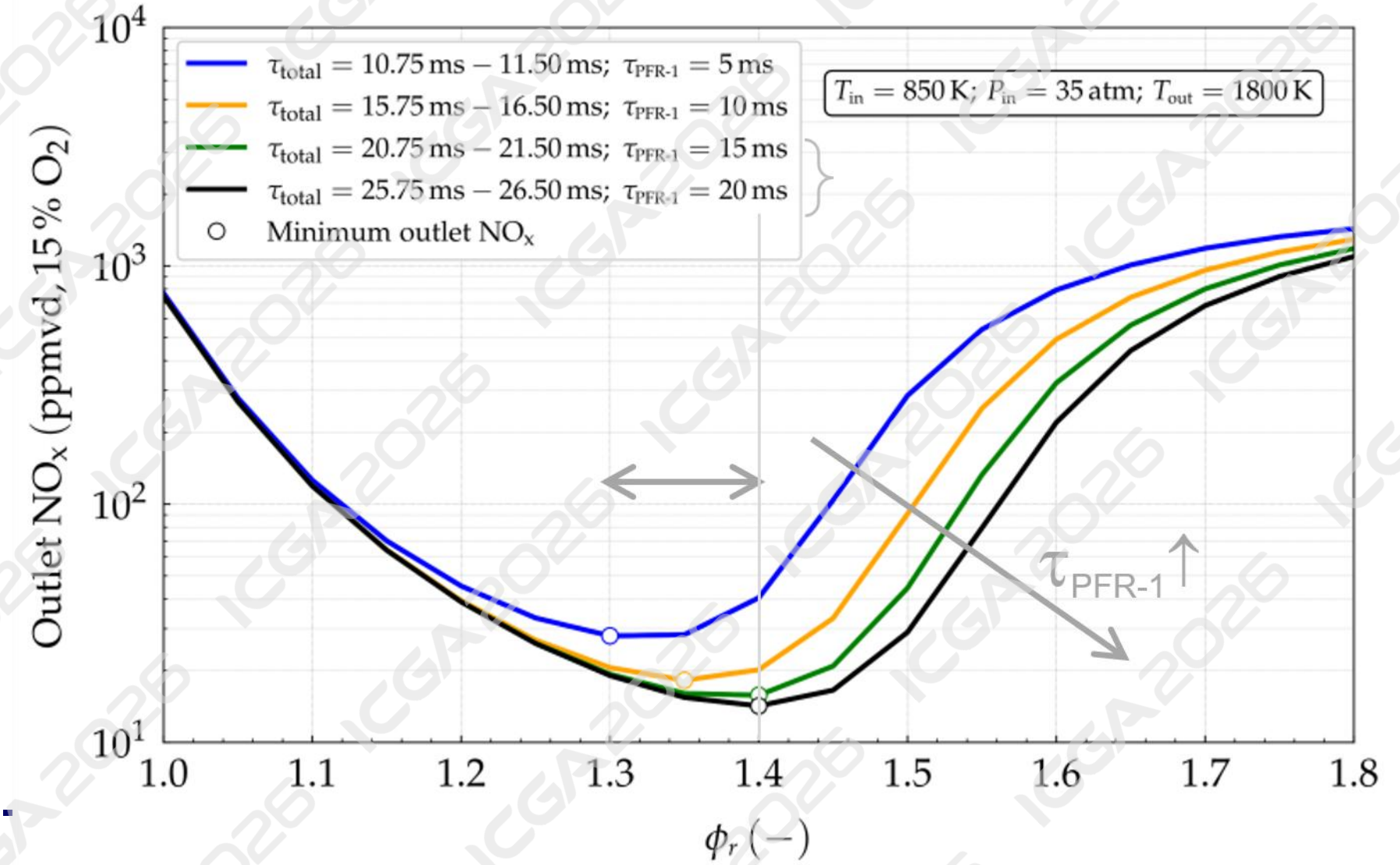


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Chemical Reactor Network (CRN) Modeling (5)

Optimal NOx Emissions: Dependence on ϕ and τ



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Chemical Reactor Network (CRN) Modeling (6)

Case	τ_{total} (ms)	τ_{PFR-1} (ms)	τ_{PFR-2} (ms)	P_{in} (atm)	T_{out} (K)	ϕ_r (-)	ϕ_l‡ (-)	Rich Stage# NH_3† (ppm)	Rich Stage# NOx* (ppm)	Lean Stage§ NH_3† (ppb)	Lean Stage§ NOx* (ppm)
A1	38.5	35	2	35	1800	1.45	0.45	17.5	4.7	0.023	12.1
A2	38.5	35	2	35	1800	1.80	0.45	6384.3	2.6	0.013	895.4
A3	38.5	35	2	35	1800	1.10	0.45	1.7	120.4	0.021	118.3
C1	11.5	5	5	35	1800	1.30	0.45	12.6	23.2	0.022	28.3
C2	41.5	35	5	35	1800	1.45	0.45	17.5	4.6	0.023	12.9
D1	41.5	35	5	35	1900	1.45	0.51	17.5	4.6	0.073	19.4
D2	38.5	35	2	35	1900	1.45	0.51	17.5	4.6	0.073	15.3
E1	11.5	5	5	20	1800	1.35	0.45	14.7	36.2	0.017	40.0
E2	41.5	35	5	20	1800	1.45	0.45	10.5	6.5	0.018	11.9
G1	11.5	5	5	40	1800	1.30	0.45	13.7	20.3	0.024	26.2
G2	41.5	35	5	40	1800	1.40	0.45	15.4	6.0	0.024	13.4

At the end of fuel-rich stage
§ At the end of fuel-lean stage
‡ Lean-stage equivalence ratio is same as global equivalence ratio
† Wet basis
* 15 % O_2 dry basis

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Development of Lab-Scale Ammonia Combustor

- Adoption of rich-burn/quick-quench/lean-burn (RQL) strategy for ammonia combustion under aero gas-turbine relevant conditions
- Application of a CRN guided, CFD modeling design approach for iterative variations in geometry and conditions
- Design of a swirl-stabilized ammonia burner
- Design optimization of rich- and lean-zone dimensions
- Design optimization of quench-jet flow split and layout
- Performance target: NO_x emissions below 30 ppmvd (at 15% O_2, humidity-corrected)

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CRN Guided, CFD Design Approach (1)



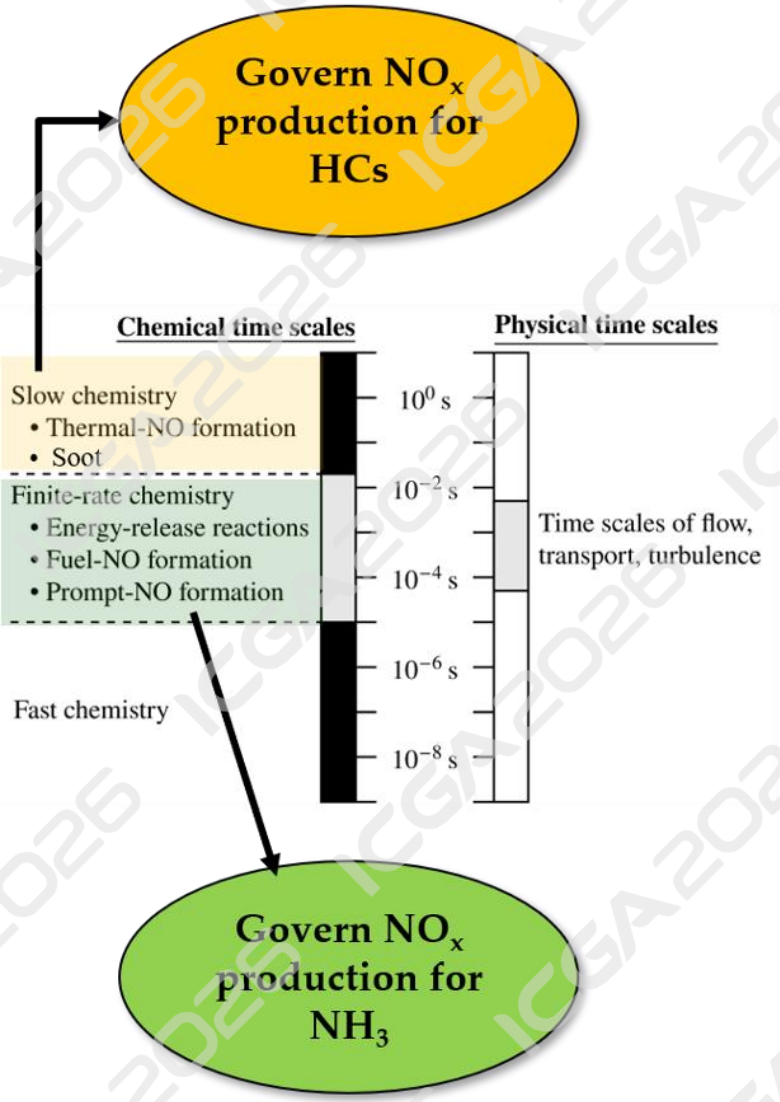
FT4000® Aeroderivative Dual Fuel Gas Turbine Engine.

Basic NH_3 injector design adapted from US Patent 12,181,153, originally developed for pure H_2 or high-H_2 content blends

- Swirler concept generation and CFD optimization for mixing and flame anchoring.
  - CRN to guide combustor preliminary layout and design.
  - CFD for combustor flame anchoring/quench jet optimization.
- Given inlet and outlet conditions for an aero gas-turbine, CRN modeling guides combustor sizing and residence time for CFD.

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CRN Guided, CFD Design Approach (2)



- CFD captures flow and mixing well, but detailed chemical kinetic models are prohibitively expensive for large design-space exploration.
- CRN models predict NO_x with high chemical fidelity but lack spatial flow resolution, missing localized effects critical to practical combustor design.
- For HCs, decoupled CFD–CRN iterative procedure can be used for pollutant prediction due to differing turbulence-chemistry time scales.

Mixing-limited

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CRN Guided, CFD Design Approach (3)

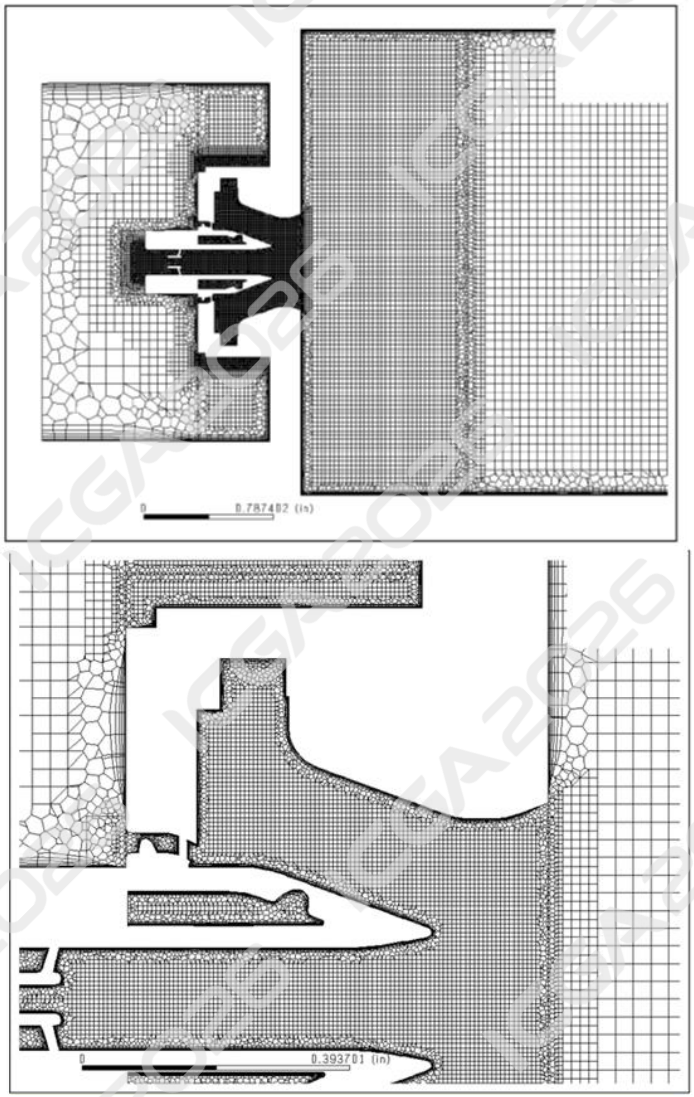


All the turbulent eddies are embedded in the reaction zone ($Da_t < 1$)

- For NH_3 flames,
  - decoupling turbulence and chemical kinetics is inappropriate due to similar flow and NO_x production chemical time-scales.
  - turbulent eddies are embedded within the reaction zone ⇒ turbulence–chemistry interaction must be modeled in CFD.
  - turbulence-chemistry interaction is modeled using the Eddy Dissipation Concept (EDC), though at high computational cost.
  - EDC assumes that chemical reactions occur within the smallest turbulent scales, where steep species and temperature gradients yield intense local mixing.

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CFD Methodology (1)



Poly-hexcore mesh with boundary-layer refinement

- Steady-state RANS simulations with realizable k-ε (RKE) turbulence closure, well-suited for strongly swirling flows.
- NH_3/air turbulent combustion modelled using EDC.
- Chemkin-CFD solver with Stagni et al. (2020) mechanism (31 species, 203 reactions) for finite-rate chemistry.
- Radiation neglected; adiabatic walls applied; appropriate for design-stage screening and emission trend analysis.
- Grid independence verified for all simulations.

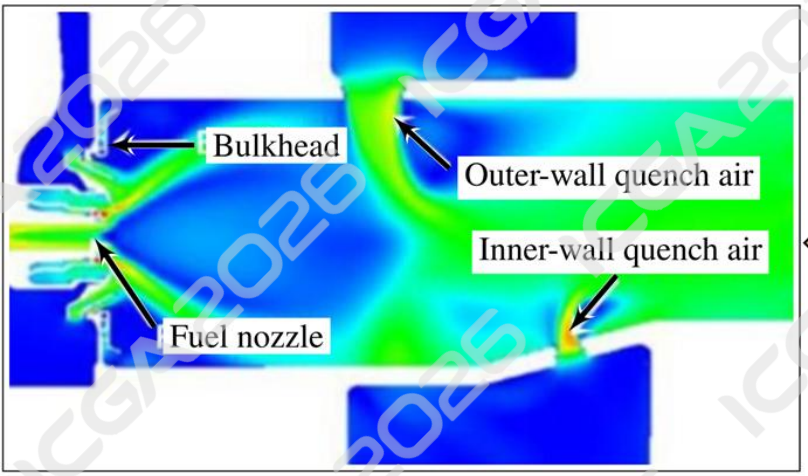
high-resolution mesh of ~8M cells, ~33M faces, and ~17M nodes

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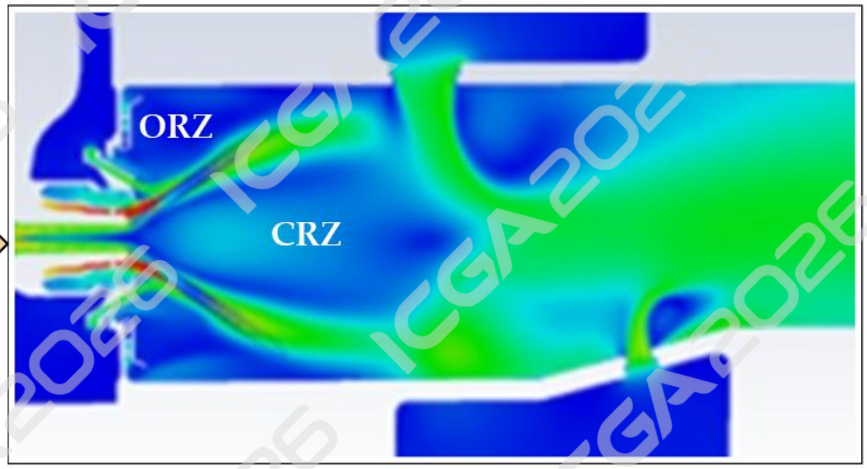
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CFD Methodology (2)

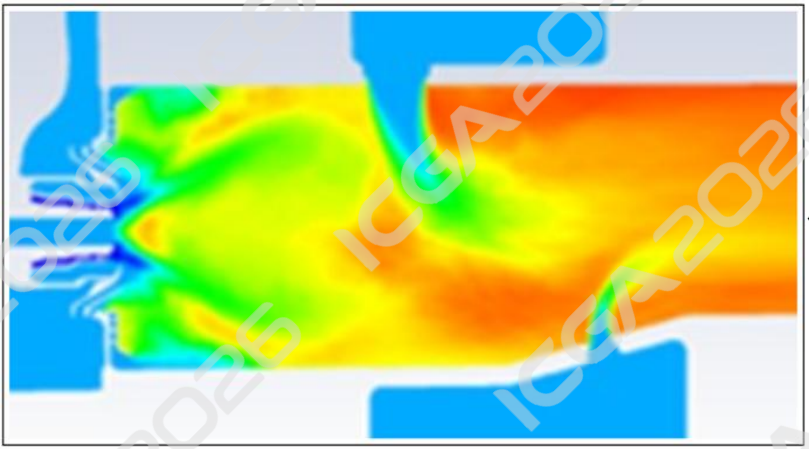
Qualitative RKE-RANS-EDC validation against an independent LES



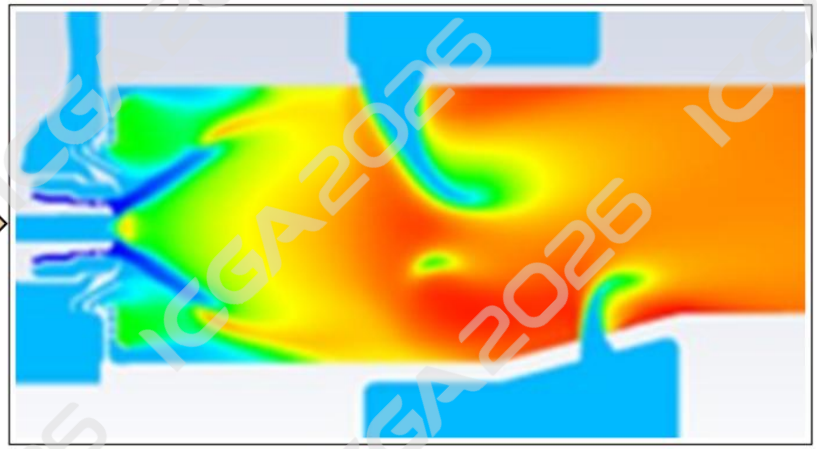
(a) LES predicted velocity field in the combustor



(b) RANS-EDC predicted velocity field in the combustor



(a) LES predicted temperature field in the combustor



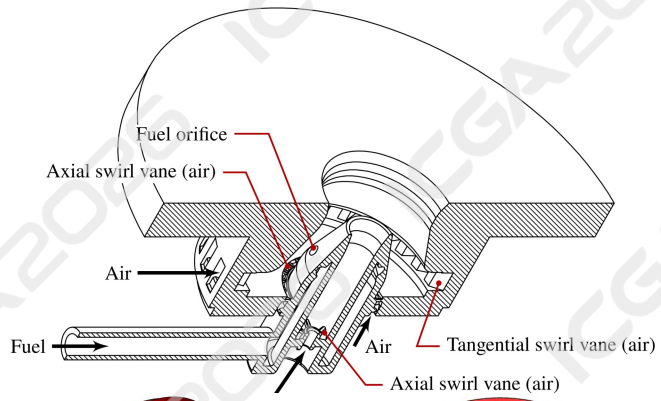
(b) RANS-EDC predicted temperature field in the combustor

CRZ: central recirculation zone *ORZ: outer recirculation zone*

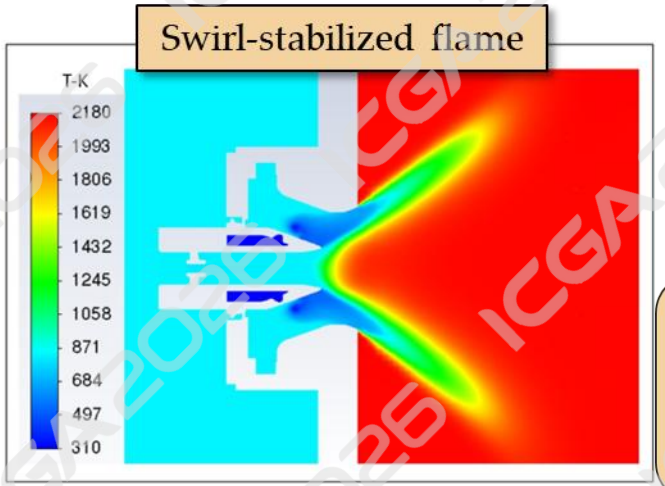
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Swirl Burner Design







- Tangential NH_3 injection aligned with air swirl ⇒ preserves swirl strength and enhances flame anchoring.
- Injector outlet flared to promote CRZ formation and enhance flame stabilization for NH_3 combustion.
- Fuel orifice sized for tip pressure drop < 8%; air swirler sized to a typical combustor dome pressure drop.
- Final design: swirl number $S_N = 0.6$, selected for flame anchoring across low- and high-pressure, high-temperature operating conditions.

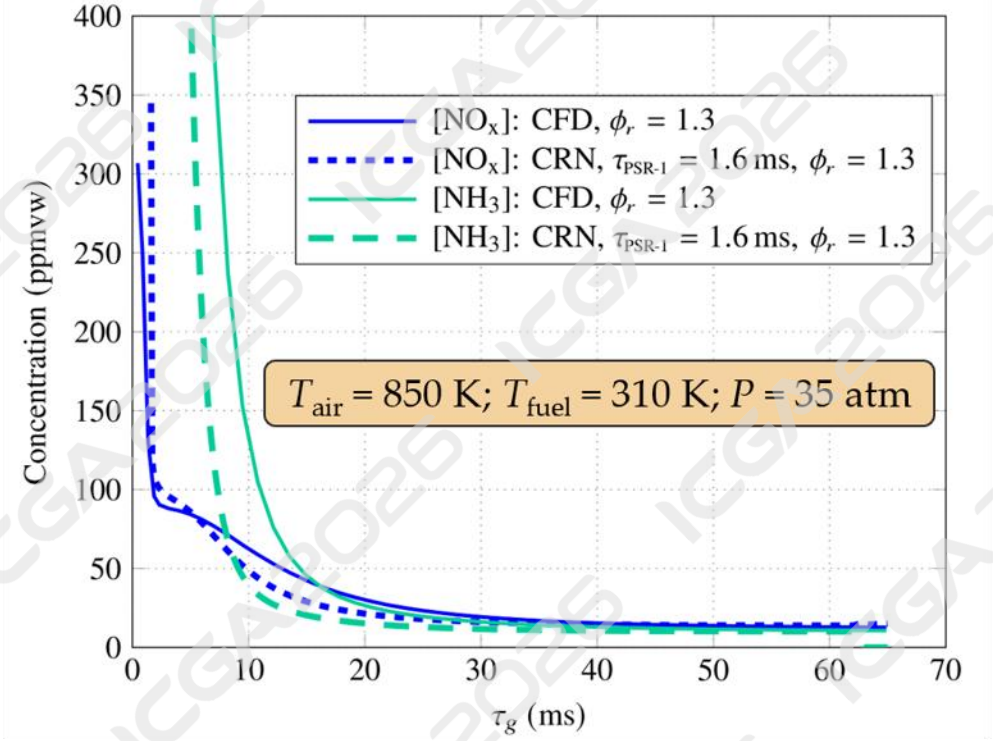
Operating Conditions Range

100% NH_3; $\dot{m}_{fuel} = 0.026$ kg/s; $T_{air} = 850$ K; $T_{fuel} = 310$ K; $T_{exit} = 1800$ K;

$P = 35$ atm; $\Delta P/P \approx 3.5\%$; $\phi_r = 1.1 - 1.7$

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Rich-Zone Design



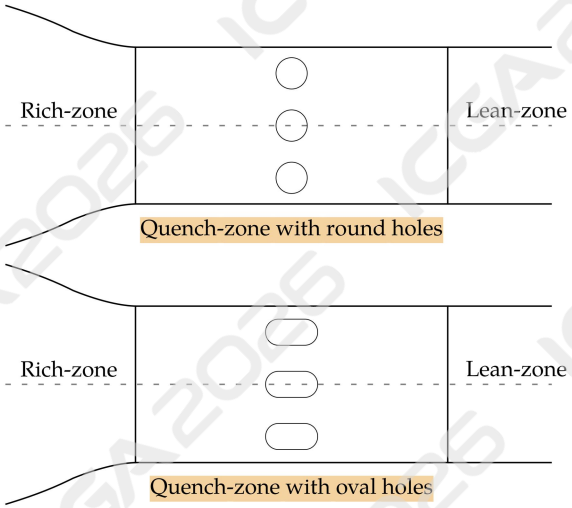
Sufficient rich-zone τ_{res} achieved using a low reference velocity in the combustor front end to reduce the required combustor length.

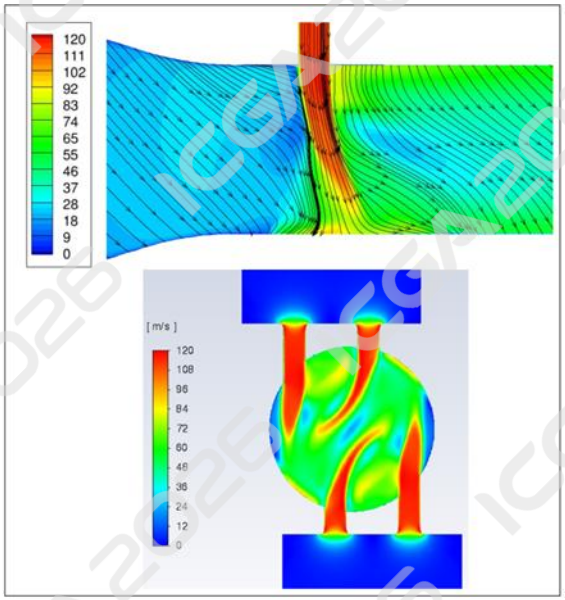
- Rich-zone τ_{res} estimated from cylindrical NH_3 combustor simulations without secondary-air quenching, maintaining stable swirl-anchored flame.
- NO_x and NH_3 below 15 ppmvw at ~35 ms residence time to ensure almost complete NH_3 cracking to H_2.

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Quench-Zone Design





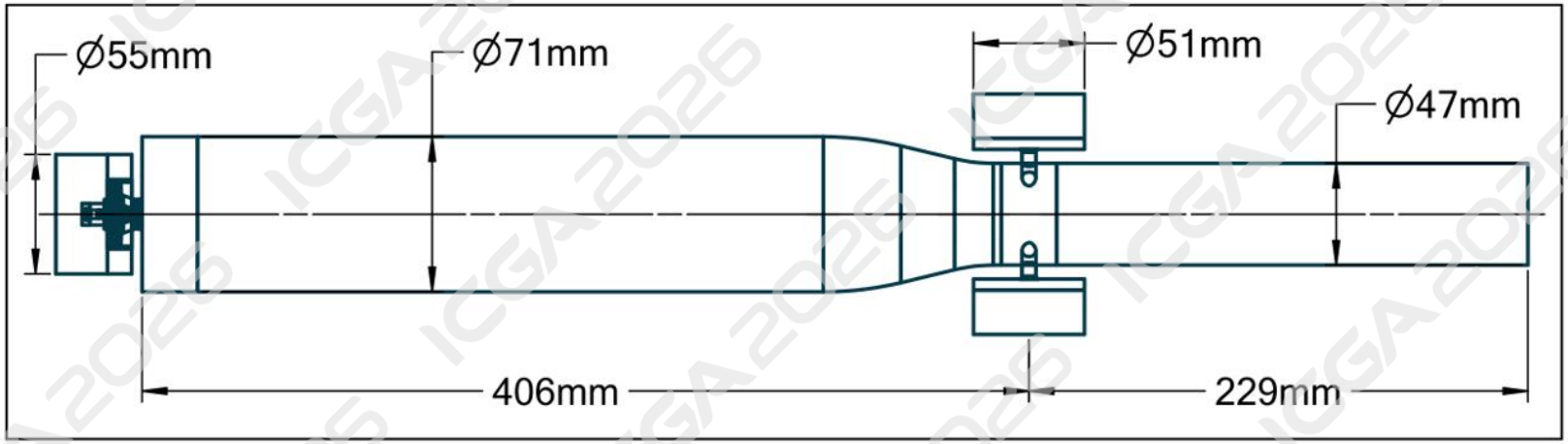
Flow field near quench jets

- Contraction section added downstream of rich-zone to prevent quench air backflow.
- Quick-mix jet penetration depends on number, spacing, shape, slant angle of orifices, axial mass addition rate, and orifice-induced swirl.
- NO_x minimization in quick-mixer: tradeoff between effective initial mixing and wall-region mixing downstream of injection plane.
- Optimized jet-to-mainstream mass-flow and momentum-flux ratios to avoid under- or over-penetration.
- Using CFD, eccentrically aligned round holes yielded the lowest NO_x quick-mixer configuration.

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Lean-Zone and Full Path Design

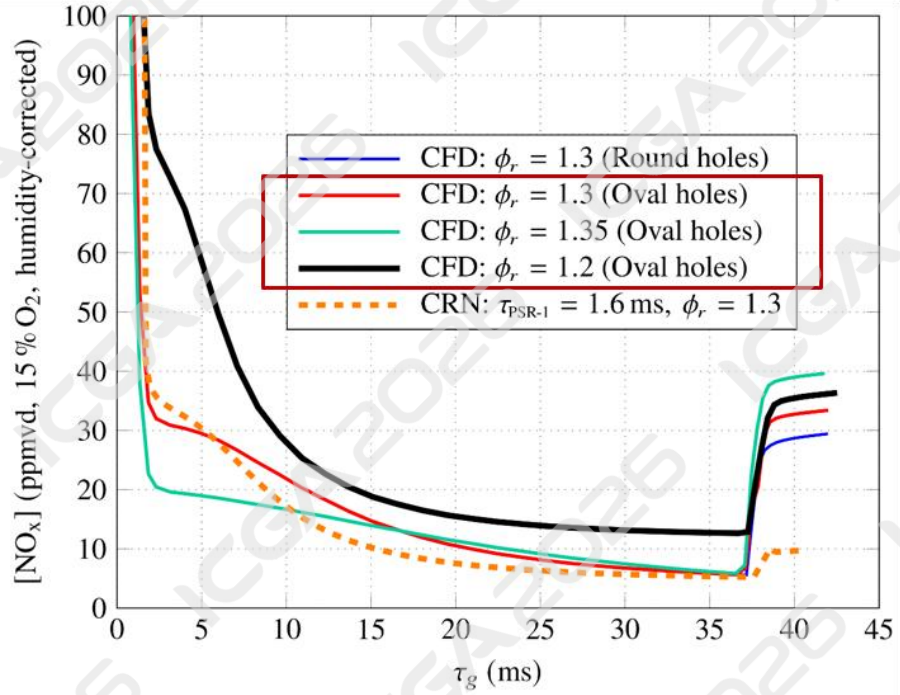


- Lean-zone length sized to minimize thermal NO_x while meeting combustion efficiency and exit temperature profile requirements.
- Total combustor length: 635 mm (injection to exhaust plane); four 6.35 mm quick-mix jets in quench zone.
- Configuration achieves optimal mixing, minimal NH_3-slip, and lowest NO_x at lean-zone outlet.

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CFD–CRN Results



- NO_x minimization most sensitive to rich-zone τ_{res} and quench-zone design.
- Oval holes cause over-penetration at given momentum flux ratio $\Rightarrow$ higher NO_x.
- CFD shows temporal NO_x species shift versus CRN; attributed to more accurate capture of fuel mixing time before equilibrium relaxation.
- Achieved $NO_x < 30$ ppmvd (15% O_2, humidity-corrected) under aero-derivative gas-turbine conditions.

100% NH_3; $\dot{m}_{fuel} = 0.026$ kg/s; $T_{air} = 850$ K; $T_{fuel} = 310$ K; $T_{exit} = 1800$ K; $P = 35$ atm

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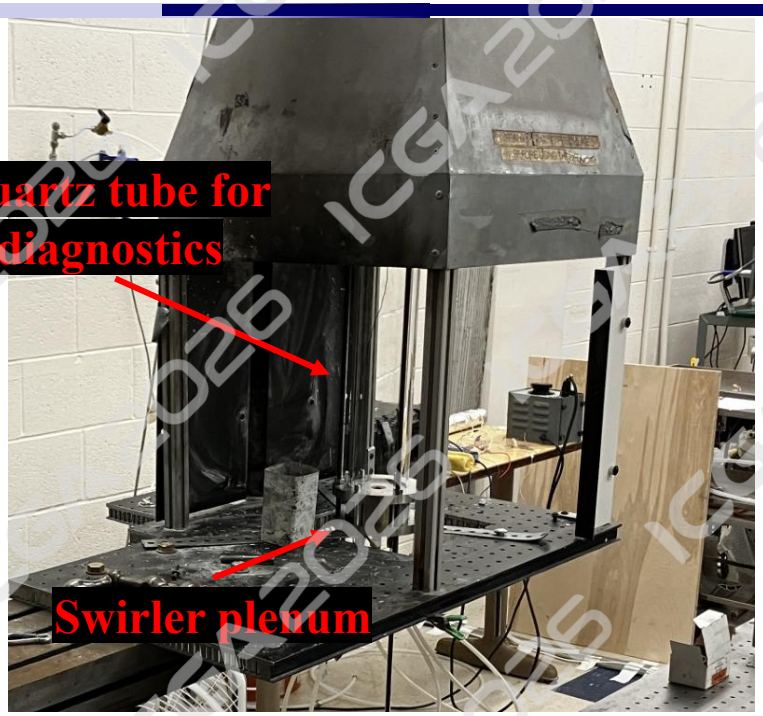
Concluding Remarks

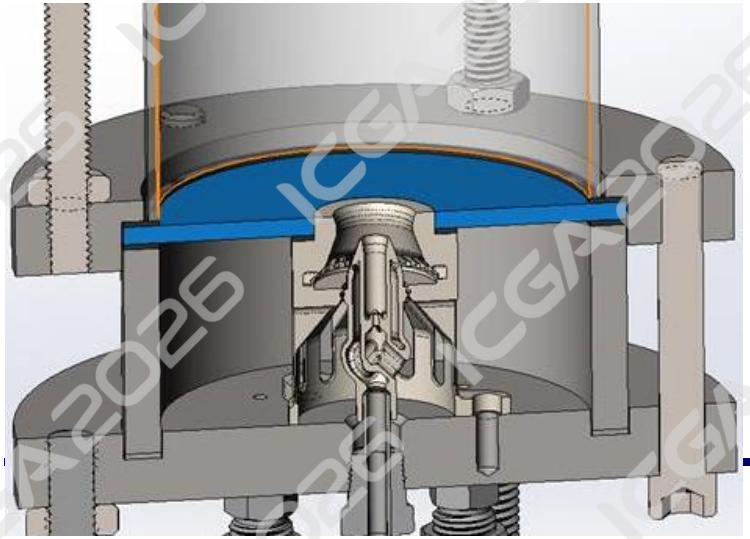
- Leveraging carbon-free fuels in advanced power and propulsion systems has the potential to reduce net CO_2 emissions.
- Aviation is difficult to de-carbonize, but new fuels offer efficiency improvements to help enable.
- Hydrogen has challenges, but brings opportunity as cryo-fuel/cryo-fluid in aviation.
- Ammonia is viable as a carbon-free, high-efficiency transportation fuel, including in aviation.
- NH_3 requires fundamentally different RQL design approach compared to conventional hydrocarbon fuels.
- Low-NO_x, NH_3 combustion achievable in RQL architecture when rich-zone τ_{res} and quench-zone mixing are co-optimized.
- A comprehensive ammonia combustion kinetics is essential for optimizing conditions to minimize NO_x emissions in high-pressure GT operations.

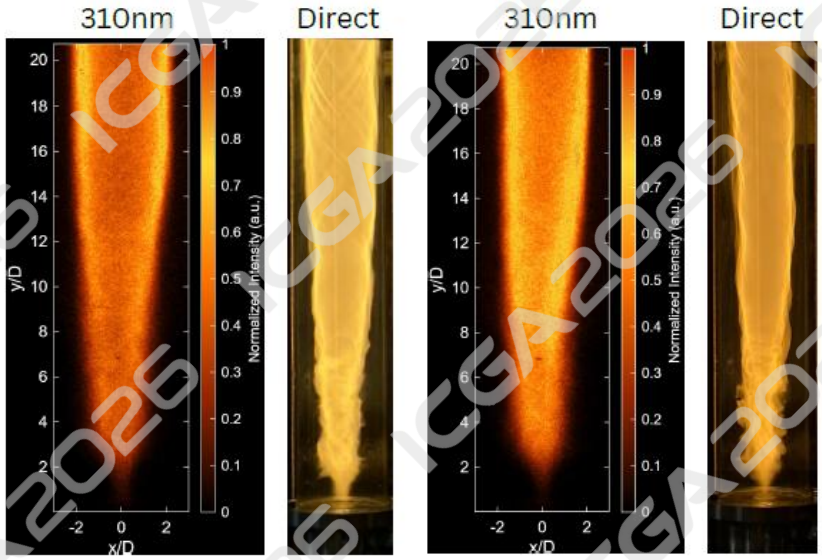
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Swirl-Stabilized Ammonia Flame Rig

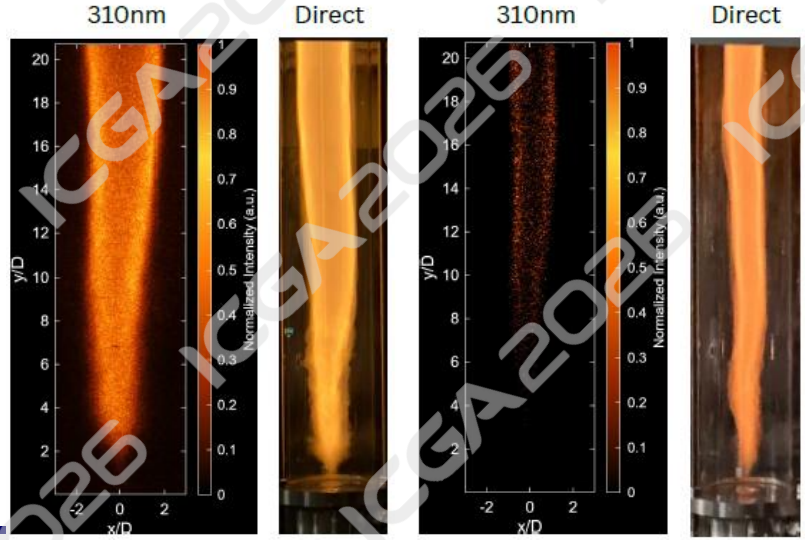






ΔP = 3%, φ = 1

ΔP = 3%, φ = .85



ΔP = 3%, φ = .75

ΔP = 3%, φ = .65